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FACTORS AFFECTING HUMAN TOLERANCE TO SUSTAINED ACCELERATION

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Six relaxed subjects were exposed on a centrifuge to increasing G pulses in order to determine their G tolerance. G protection was provided by supination and/or inflation of anti-G suit (AGS) bladders using a newly developed rapid response, servo controlled anti-G (SCAG) valve. Supination, alone or with the AGS, was most effective in increasing G tolerance. Increases in SCAG Valve outlet pressure were directly related to increases in G tolerance. Neither of two modes of SCAG valve operation caused any significant difference in G tolerance nor in assessment of AGS comfort. When protected by supination and

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

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INTRODUCTION The occasional, unexplained loss of a high-performance aircraft has given rise to speculation about the role played by G-induced loss of consciousness. This speculation is not without merit, considering that modern fighters are capable of exposing pilots to significant G loads at rates which far exceed those of even the recent past. While thrust-to-weight ratios of high-performance aircraft have increased appreciably over the past couple of decades, improvements in hardware systems for protecting the pilot against adverse G effects are only now being implemented. In fact, present day G-protective equipment used in military aircraft is not much different from that developed during World War II.

The most effective method of providing G protection has been shown to be supination of the pilot's body, so that Gz loads are transformed into Gx loads which are better tolerated. Unfortunately, implementation of this technique has met with considerable resistance because of the drastic changes in cockpit configuration which would be required, including modification and relocation of displays and controls and replacement of the present ejection seat. Partial supination, however, may be more easily achieved, and it is likely that future high-performance aircraft will incorporate design changes necessary for this to be accomplished. Another way to improve G tolerance lies in the improvement of the anti-G valve (AGV). Serious efforts are now underway to modify the standard AGV in order to reduce the lag between G load and inflation of the anti-G suit (AGS) bladders. In addition, new AGVs have been designed which are much more responsive to G load, and can be made to respond to other inputs from the flight environment, so that anticipatory actions can be taken to provide more effective G protection. One such valve is the servo-controlled anti-G (SCAG) valve, a prototype model of which was used in the present study.

There is presently little information available on AGV outlet pressures which applies to any body position other than upright. The purpose for conducting this study was to obtain data on SCAG valve outlet pressure in the supinated and upright body positions, using G tolerance and AGS comfort as dependent variables. In addition, the effects of mode of SCAG valve operation and acceleration onset time were included in the experimental design.

METHOD

Subjects Before initiating the experimental portions of this study, a group of potential subjects who had been examined by a flight surgeon and found to be physically qualified were informed about the purpose of the study and the possible hazards involved. The protocol and safety procedures to be followed were formally reviewed and approved by the Naval Air Development Center (NADC) Committee for the Protection of Human Subjects. The informed, written consent of the six individuals who volunteered to participate as subjects was then obtained. Some of the physical characteristics of these subjects are listed in Table 1. All of the subjects were naval enlisted personnel and were familiar with the equipment to be used and the procedures to be followed.

Table 1. Subject Characteristics

Subject	Sex	Age (yr)	Height (cm)	Weight (kg)	Sitting Height (cm)	Shoulder Height (cm)
1	M	28	172.7	73.6	90.9	61.0*
2	M	19	182.9	84.1	94.5	63.8
3	F	21	167.6	59.1	88.1	57.6
4	M	23	190.5	93.2	98.3	69.2
5	M	23	175.3	75.0	90.9	62.8
6	M	25	172.7	68.1	90.2	59.6

* Estimated

Subject Preparation and Body Position Prior to entering the gondola of the NADC human centifuge, (Figure 1), ECG electrodes were attached to the subject's torso, a remotely operated blood pressure cuff containing a microphone was placed on his upper arm, and a Doppler transceiver was fixed to the skin of his forehead overlying a branch of the temporal artery. The subject wore shoes and socks, underwear, a flight suit, and a carefully fitted CSU-15/P AGS. After entering the gondola, the subject was restrained by a torso harness in the Pelvis and Leg Elevating (PALE) seat and the NADC curved light bar was positioned to encircle his head, as shown in Figure 2. The PALE seat is articulated so that its supporting parts can be positioned from a full upright configuration, similar to that of a standard aircraft ejection seat, to a fully reclined configuration on which the subject's body is completely supinated. These changes in body position are accomplished without changing the subject's eye position with respect to his surrounding environment (Figure 3). In this study, the PALE seat was adjusted so that the seat back assumed either a 15 degree seat back angle (referred to as "upright") or a 60 degree seat back angle (referred to as "supine").

G Tolerance Limit The NADC curved light bar shown in Figure 2 is operated by the subject and provides a continuous measurement of his peripheral vision in the plane of the bar. During use, the subject fixates on a central white light mounted on the bar directly in front of the bridge of his nose. By exerting force on a two-axis, side arm controller with his right hand, he controls the lighting of any single pair of the 60 pairs of red light emitting diodes (LEDs) installed along the bar at 1.5 degree intervals. The subject is instructed to maintain a pair of lighted LEDs located at the outermost limits of his peripheral visual field at a subjectively determined level of constant brightness. As his visual field constricts during G, he proportionately reduces his pull on the side arm control handle. This allows more anteriorly located pairs of LEDs to light on each side of the central light, thereby progressively reducing the angle subtended by the lighted pairs of LEDs. If he fails at any time to exert pull on the control handle, the pairs of illuminated LEDs automatically converge toward the central white light at the rate of 60 degrees per second. For this study, a cut-off of 60 degrees on the light bar (i.e., 30 degrees on each side of the central light) was established as the visual angle which automatically stopped the centrifuge arm. The G plateau level at which this occurred was used, as will be described, in determining the subject's G tolerance limit. (The phrase "G tolerance limit" is usually shortened to "G tolerance" in this report). Thus, in the event that the subject failed to pull on the control handle during G, when the most peripherally located pair of LEDs were lit, one second would elapse before the centrifuge arm would be placed in its automatic stop mode. The subjects were trained to operate the light bar control in both the upright and supine body positions.

SCAG Valve The bladders of the AGS were inflated with air, and deflated, by means of recently developed SCAG valve. This valve is servo-controlled and depends for its action upon the amplified voltage difference between the output of an accelerometer, which

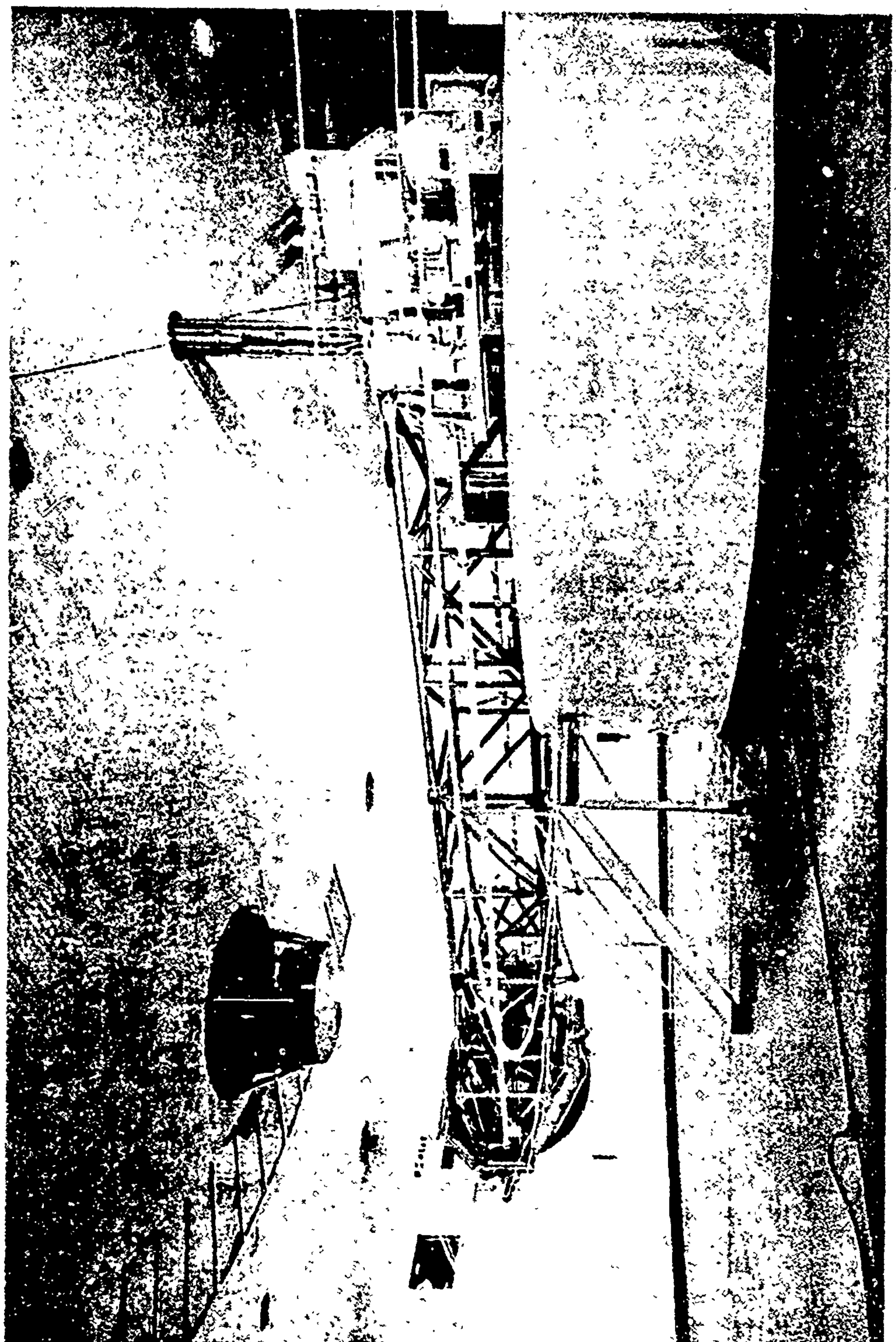

Figure 1. Human Centrifuge of the Naval Air Development Center's Dynamic Flight Simulator.

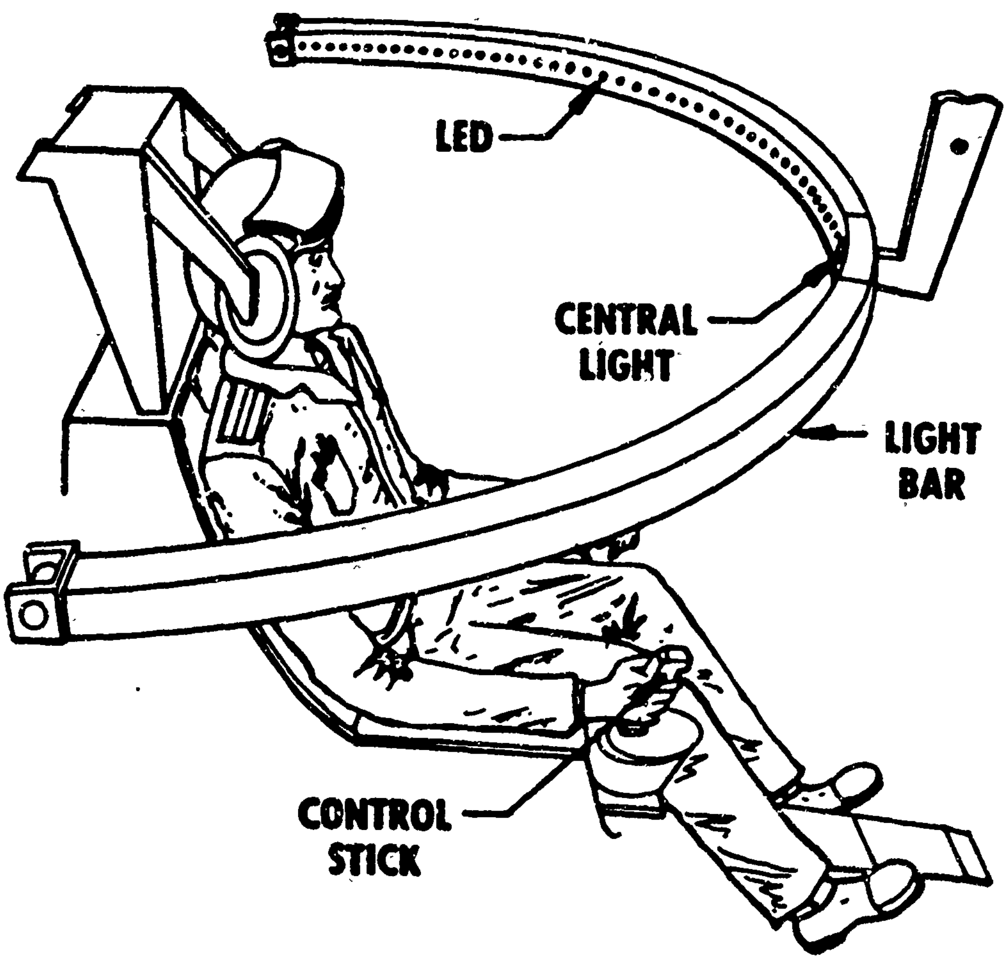

Figure 2. NADC curved light bar used to determine G-tolerance by peripheral light loss.

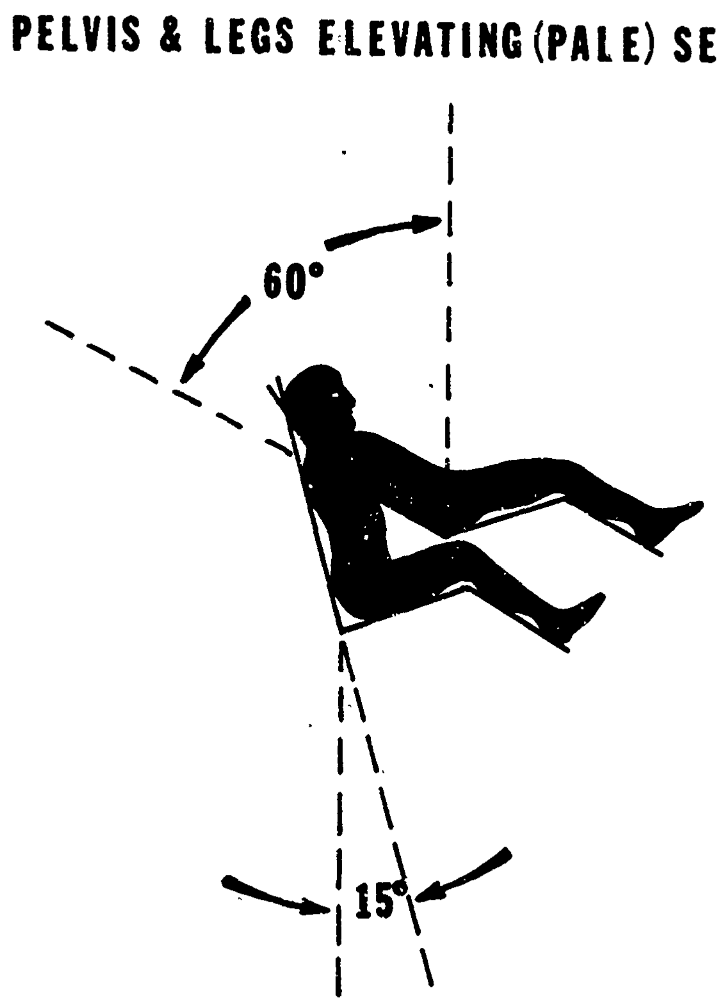

Figure 3. Diagram of change in body position using the PALE seat.

senses G, and a pressure transducer, which senses the pressure inflating the AGS bladders. Amplifier gain is adjusted to maintain maximum loop stability and minimum pressure lag. A more complete description of the SCAG valve and its performance has been reported (4). For this study, two modes of SCAG valve operation were used (Figure 4). In mode I, feedback derived from AGS inlet hose pressure controlled valve output, so that valve outlet pressure was practically concurrent with, and directly proportional to, G loading. In mode B, the initial phase of valve outlet pressure was enhanced (simulating feedback from a pressure sensor located in the abdominal bladder of the AGS), so that valve outlet pressure transiently overshot the level which would have been provided if the valve were acting in the I mode. The net effect of this enhancement was to decrease the lag, by several hundred milliseconds, between the start of G onset and the beginning of abdominal bladder pressurization.

AGV Outlet Pressure The AGV outlet pressure versus G schedule utilized was based upon results obtained from an earlier series of tests in which the SCAG valve was used (4). In the earlier tests, G tolerance was determined from recordings of temporal artery mean blood flow velocity, measured with a Doppler tranceiver in a manner similar to that already described in this report. The AGV schedule developed was based upon the following equations:

$$P = 1.5\ (G - 1) \cos\ (\theta - 15) \qquad (1)$$

where P is the AGV outlet pressure in psig and equals 0 when $G < 1.5$, G is the resultant G (see Appendix A), and θ is the seat back angle in degrees. When $\theta = 15$, equation (1) reduces to:

$$P = 1.5\ (G - 1) \qquad (2)$$

Equation (2) is the middle curve shown in the left portion of Figure 5, and 1.50 psig/G was used in the present study as the "middle" level pressure gradient for the upright body position. Two other gradients, one 25 percent greater than, and the other 25 percent less than the middle level were also evaluated. The two curves incorporating these gradients are also shown in the left portion of Figure 5, the former referred to as "high" and the latter as "low". For comparison, the schedule which the military AGV must meet is shown by the stippled area in Figure 5. This schedule was taken from the pertinent military specification issued by the U.S. Department of Defense (7). Application of equation (1) for the 60 degree seat back angle results in:

$$P = 1.06\ (G - 1) \qquad (3)$$

Equation (3) is represented by the middle curve in the right portion of Figure 5. Again, curves with 25 percent greater and lesser gradients are shown above and below the middle level gradient curve. No official publication specifies AGV outlet pressures for any body position other than upright.

Bioinstrumentation and Safety Lighting in the centrifuge gondola was subdued and a closed-circuit, low light level video camera provided continuous viewing of the subject's head on video

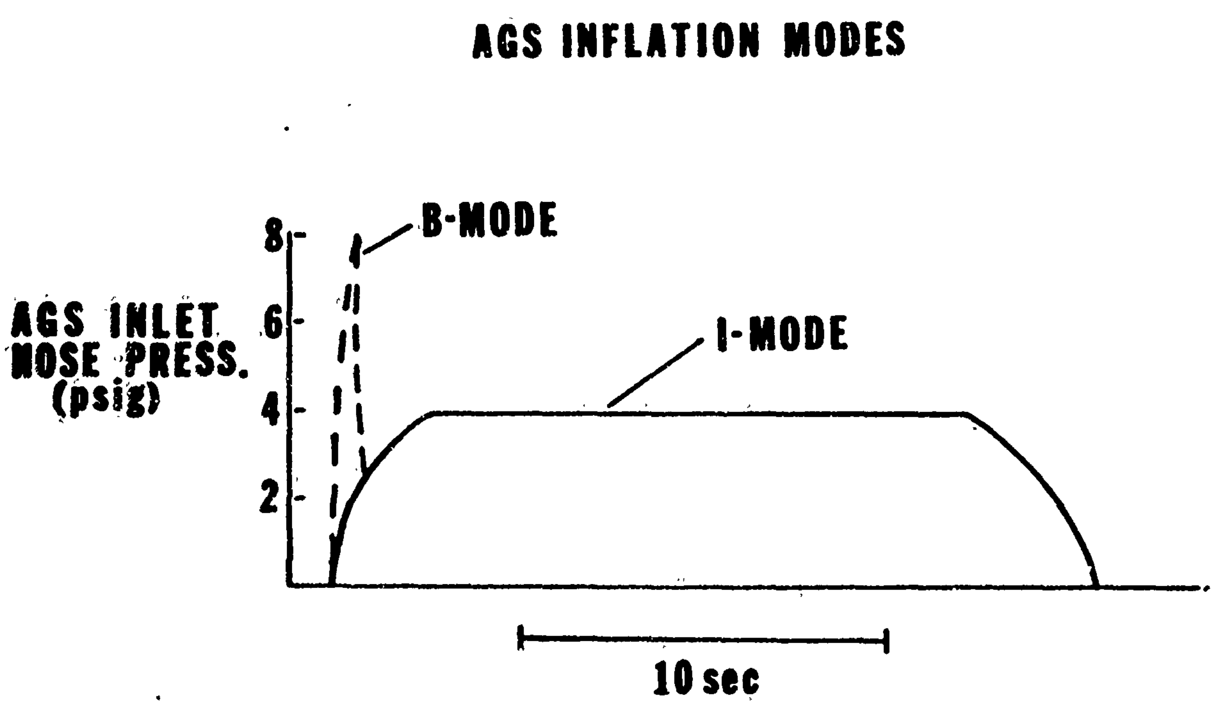

Figure 4. Modes of SCAG valve operations. B-mode causes initial transient overshoot in AGS inlet hose pressure (valve outlet pressure) which I-mode lacks.

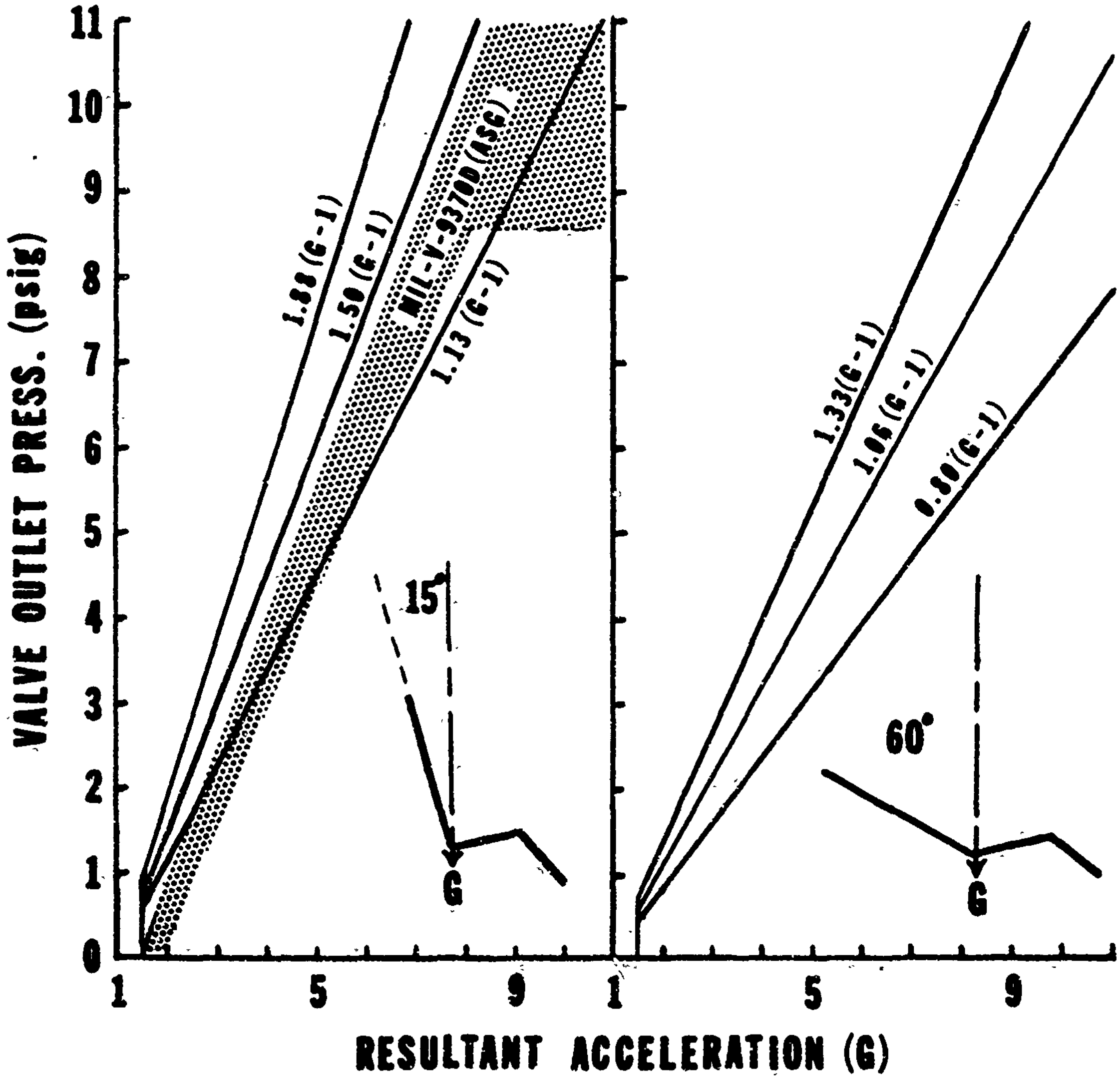

Figure 5. Valve outlet pressure schedules used for upright and supine body positions. Shaded area shows anti-G valve outlet pressures specified by MILSPEC MIL-V-93700D (AGS).

monitors used by the centrifuge operators and project personnel. Two-way oral communication with the subject was maintained throughout the runs. Strip-chart recordings of applied G, mean and pulsatile blood flow velocity, displacements of the LED pairs on the light bar, SCAG valve outlet pressure, electrocardiograms, and heart rate were made; this information and the verbal communication with the subject were also recorded on magnetic tape. Intermittent blood pressure measurements were recorded on paper tape by the medical monitor. Applied G and heart rate were presented continuously on LED displays for viewing by project observers, and an audio rendition of Doppler transceiver output was broadcast during each acceleration run.

Procedure After the subject was seated and restrained in the gondola, and the bioinstrumentation, visual light bar, communications, G-protective system, and safety systems checked for proper function, the gondola door was closed and the centrifuge arm was activated. Before and after all acceleration runs, the arm continued to turn slowly, applying 1.03 G as a baseline acceleration. An initial plateau level of 2.5 G for the upright, and 3.5 G for the supine body position was selected for the first ride for each subject. Subsequent plateau starting levels depended upon consideration of the particular subject's past performance.

The acceleration profiles, for each set of conditions shown in Table 2, consisted of haversine-shaped onsets and offsets of acceleration over time, lasting 2, 4, or 8 s, with 15 s plateaus interposed. The subject began controlling the peripheral lights 15 s before the onset of the acceleration profile; a 5 s countdown preceded the beginning of G onset. For 15 s after the completion of acceleration offset, the subject continued to control the peripheral lights. If the subject successfully tolerated the acceleration profile, the next run was made with the plateau increased by 0.5 G. This procedure was repeated until the subject was unable to complete the 15 s plateau period, that is, his visual angle, as measured on the curved light bar, had contracted to 60 degrees (or less). The procedure of determining the G tolerance limit was repeated three times per day per subject, each time with a different combination of independent variables, as shown in Table 2. Rest periods of at least 1.5 min separated successive runs. Runs were repeated in cases where subjects inadvertently lessened their pull on the side-arm controller, thereby allowing the LED pairs to converge to the 60 degree position and automatically stop the run.

Calculation of G tolerance The following formula was used to calculate G tolerance:

$$G = G_{15} + 0.5\ (T - 0.5T_o/T_o + 15) \qquad (4)$$

where,

G = G tolerance (G)
G_{15} = highest G plateau tolerated for 15 s (G)
T = Duration of exposure to highest G plateau from its start at 1.03 G to PLL (peripheral light loss endpoint) (s)
T_o = onset time of G profile for which T was measured (s)

Table 2. Order of Daily PLL Threshold Condition Combinations

(see footnote for meaning of table entries)

	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY 6	DAY 7
	SBA=15^{o}	SBA=60^{o}	SBA=15^{o}	SBA=60^{o}	SBA=15^{o}	SBA=60^{o}	SBA=15^{o}
S1	4I1.9 2I1.1 8B1.9	4I1.5 2 – 0 4I1.9	8B1.5 2I1.9 2B1.5	2I1.5 4B1.1 4I1.1	2B1.9 4B1.5 2 – 0	4B1.9 8B1.9 2B1.1	4B1.9 8 – 0 4I1.1
S2	2I1.5 2I1.9 4B1.5	2B1.5 2B1.9 8I1.5	4I1.9 4B1.9 2B1.1	2 – 0 2I1.9 8B1.9	8B1.1 8I1.9 4I1.5	4B1.5 8B1.5 4B1.9	2B1.5 8B1.9 8 – 0
S3	2B1.5 8I1.5 8B1.5	4 – 0 8I1.1 8B1.9	8B1.1 4I1.5 8I1.9	8B1.1 8B1.5 4I1.1	2I1.1 4B1.5 2I1.9	4B1.5 4I1.9 2B1.1	8 – 0 2B1.9 8I1.1
S4	8I1.9 8 – 0 4I1.9	2B1.5 8B1.9 4 – 0	8B1.9 2I1.9 4 – 0	2I1.9 4B1.1 4I1.9	8I1.1 4B1.5 8B1.5	8I1.1 4I1.5 8I1.5	2 – 0 2I1.5 2B1.5
S5	4I1.5 8I1.5 8 – 0	8B1.5 2B1.9 2I1.5	4B1.1 2B1.9 2 – 0	4B1.5 2I1.1 8I1.5	2I1.1 2I1.5 8B1.9	8B1.9 4 – 0 8I1.9	2B1.1 4B1.9 4 – 0
S6	4B1.9 8I1.9 4B1.1	4B1.9 2 – 0 8I1.1	8 – 0 2B1.1 4B1.5	8B1.9 4B1.1 8I1.5	4I1.5 4 – 0 8B1.1	8I1.9 4B1.5 8B1.5	2B1.9 2I1.5 2B.15

Table 2. Cont'd

	DAY 8	DAY 9	DAY 10	DAY 11	DAY 12	DAY 13	DAY 14
	SBA=60°	SBA=15°	SBA=60°	SBA=15°	SBA=60°	SBA=15°	SBA=60°
S1	2B1.9 8 – 0 4 – 0	4B1.1 8B1.1 8I1.9	8B1.1 8I1.9 8I1.5	2I1.5 8I1.5 4 – 0	2I1.9 4B1.5 2I1.1	2B1.1 4I1.5 8I1.1	8I1.1 2B1.5 8B1.5
S2	2B1.1 4I1.1 4 – 0	2B1.9 8B1.5 2I1.1	4I1.9 4B1.1 8 – 0	2 – 0 8I1.5 4B1.1	2I1.5 8B1.1 8I1.1	8I1.1 4 – 0 4I1.1	2I1.1 8I1.9 4I1.5
S3	8I1.5 8 – 0 4B1.9	4 – 0 2B1.1 4B1.9	2B1.5 4I1.5 2I1.9	8B1.9 2 – 0 4I1.1	2I1.1 2 – 0 2B1.9	2I1.5 4B1.1 4I1.9	2I1.5 4B1.1 8I1.9
S4	2B1.9 2 – 0 8B1.5	4B1.9 2B1.9 2B1.1	8 – 0 8I1.9 2I1.1	8I1.5 4B1.1 2I1.1	2B1.1 8B1.1 4B1.9	8B1.1 4I1.1 4I1.5	4B1.5 4I1.1 2I1.5
S5	8 – 0 2B1.5 4B1.9	8B1.1 2B1.5 8I1.1	4I1.5 4I1.9 8I1.1	8I1.9 4I1.1 4I1.9	4I1.1 8B1.1 2B1.1	4B1.5 8B1.5 2I1.9	2 – 0 2I1.9 4B1.1
S6	2I1.9 2I1.1 2I1.5	2 – 0 8B1.5 8I1.1	8B1.9 2B1.1 4 – 0	4I1.9 2I1.9 8I1.5	2B1.9 4I1.5 8 – 0	8B1.9 2I1.1 4I1.1	4I1.9 2B1.5 4I1.1

Each entry in table specifies levels of 3 variables:

First numeral: Haversine onset time in seconds.

Second letter: I = AGS inflation controlled by suit inlet pressure; B = AGS inflation controlled by simulated bladder pressure feedback; – = suit not inflated.

Third set of numerals: Approximation of AGS pressurization gradient in psig/G: 0 = AGS not inflated; 1.1 = 1.13 for SBA = 15° and 1.06 for SBA = 60°; 0.8 = 0.80; 1.3 = 1.33; 1.5 = 1.50; 1.9 = 1.88.

In essence, this formula assumes a symmetrical S-shaped onset of the G-time profile, adds one-half of the onset G-time to the plateau G-time until PLL occurs, and then uses this value to determine the proportion of the 0.5 G step increase between successive runs to be added to the highest G plateau tolerated for 15 s. This procedure differs slightly from that used by Crosbie (4), who utilized the complete G-time profile, including the entire G-time onset segment, in determing the proportion of the 0.5 G step increase to be added to the highest plateau tolerated for 15 s. Since Crosbie was concerned with only 3 s onset times, his calculated G tolerance values are 0.04 G greater than those calculated by using equation (1). However, for longer onset times, a more appreciable discrepancy would result if the entire onset time (.09 G for the 8 s onset time used in the present study) were included in calculating G tolerance.

Comfort Assessment The subjects were required to evaluate and report AGS comfort following each run for which a tolerance threshold was determined. In order to assist the subject in rating AGS comfort, a copy of the numerical scale and adjective equivalents was installed within the subject's view inside the gondola. This scale extended linearly from 0 to 100 with the following equivalents: 0, very poor; 25, poor; 50, fair; 75, good; 100, excellent. Following the completion of the threshold determining run, the subjects made a numerical rating of AGS comfort and commented upon any particular aspects relating to comfort which they believed to be pertinent. These reports were entered on the form shown as Figure 6 by the project officer.

Experimental Design The overall scheme, showing the order and condition combinations for each series of runs leading to a G tolerance threshold determination is shown in Table 2. A table of random numbers was used in formulating the order in which condition combinations were imposed. Two to five separate runs were required per subject to arrive at the tolerance endpoint for each combination of conditions. Each subject rode the centrifuge once per day, in accordance with the schedule shown in Table 3. Occasional deviations from the scheduled order shown in Tables 2 and 3 were necessitated by events over which the investigators had no control.

RESULTS

G tolerance The G tolerance means and their standard errors for the group of six subjects are given in Table 4. An analysis of variance using the original data (Table 5) shows the significant factors to be Body Position, Valve Outlet Pressure, and G Onset Time.

Body Position: As expected, this factor had the most drastic effect on G tolerance. As shown in Figure 7, the mean upright tolerance of the group of subjects was increased from 3.13 + 0.10 G (variation about the mean is expressed in this report as standard error) to 4.80 + 0.16 G when the body position was changed from upright to supine, without inflation of the AGS bladders. This change in body positions therefore resulted in an increase of about 53 percent in G tolerance. When the AGS bladders were inflated, mean G tolerance increased from 4.30 +

DATE ______________

NAME ______________

RATE THE COMFORT OF THE ANTI-G SUIT AFTER EACH G THRESHOLD RUN.

	VERY POOR	POOR	FAIR	GOOD	EXCELLENT
FIRST THRESHOLD RUN	0	25	50	75	100

COMMENTS: ______________

____

____

	VERY POOR	POOR	FAIR	GOOD	EXCELLENT
SECOND THRESHOLD RUN	0	25	50	75	100

COMMENTS: ______________

____

____

	VERY POOR	POOR	FAIR	GOOD	EXCELLENT
THIRD THRESHOLD RUN	0	25	50	75	100

COMMENTS: ______________

____

____

Figure 6 - Form used to rate AGS comfort following each G-tolerance threshold limit run.

Table 3. Daily Order of Subject Exposure Riding DFS

Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
S1	S5	S2	S3	S4	S6	S3
S2	S4	S3	S5	S6	S1	S5
S3	S6	S1	S2	S5	S4	S2
S4	S1	S5	S6	S2	S3	S6
S5	S3	S6	S4	S1	S2	S4
S6	S2	S4	S1	S3	S5	S1

Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14
S1	S6	S4	S2	S5	S3	S1
S2	S1	S6	S3	S4	S5	S2
S3	S4	S5	S1	S6	S2	S3
S4	S3	S2	S5	S1	S6	S4
S5	S2	S1	S6	S3	S4	S5
S6	S5	S3	S4	S2	S1	S6

Table 4. G Tolerance Thresholds (Means ± SEM, N = 6)

Valve Outlet Press	Upright G Onset Time (s)						Supine G Onset Time (s)					
	2		4		8		2		4		8	
0	3.17 ± .20		3.09 ± .16		3.12 ± .18		4.82 ± .27		4.95 ± .33		4.63 ± .28	
	Mode*		Mode		Mode		Mode		Mode		Mode	
	I	B	I	B	I	B	I	B	I	B	I	B
Low	4.11 ±.27	4.05 ±.19	4.07 ±.30	4.06 ±.30	4.21 ±.22	3.96 ±.27	6.30 ±.47	6.15 ±.54	6.04 ±.44	6.09 ±.37	5.60 ±.28	5.65 ±.46
Medium	4.61 ±.27	4.42 ±.24	4.21 ±.30	4.17 ±.22	4.24 ±.28	4.08 ±.17	6.62 ±.44	6.32 ±.36	6.30 ±.40	6.39 ±.36	5.83 ±.39	6.00 ±.37
High	4.55 ±.30	4.54 ±.27	4.45 ±.37	4.53 ±.29	4.54 ±.38	4.52 ±.29	6.73 ±.41	6.87 ±.54	6.53 ±.45	6.17 ±.37	6.57 ±.41	6.16 ±.33

*Mode is described in the text.

Table 5. Analysis of Variance of G Tolerance

Source	df	Sum of Squares	Mean Square	F[a]
Onset Time (O)	2	3.922	1.961	7.98**
Press. Gradient (P)	2	8.637	4.319	64.46***
Valve Mode (V)	1	0.239	0.239	1.54
Body Position (B)	1	205.901	205.901	113.69***
Subjects (S)[b]	5	95.037	19.007	—
OP	4	0.634	0.159	1.03
OV	2	0.114	0.057	
VP	2	0.028	0.014	
OB	2	1.686	0.843	3.03
PB	2	0.093	0.047	
VB	1	0.006	0.006	
SO	10	2.456	0.246	—
SP	10	0.669	0.067	—
SV	5	0.777	0.155	—
SB	5	9.054	1.811	—
OPV	4	0.586	0.146	1.19
OPB	4	0.920	0.230	2.09

Cont'd

Table 5. Cont'd

Source	df	Sum of Squares	Mean Square	F[a]
OVB	2	0.109	0.055	
PVB	2	0.285	0.142	
SOP	20	3.094	0.155	—
SVO	10	2.925	0.292	—
SPV	10	2.626	0.263	—
SBO	10	2.783	0.278	—
SBP	10	1.541	0.154	—
SBV	5	1.625	0.325	—
OPVB	4	0.513	0.128	1.42
SVPO	20	2.465	0.123	—
SBPO	20	2.195	0.110	—
SBVO	10	4.004	0.400	—
SBVP	10	1.988	0.199	—
SBVPO	20	1.807	0.090	—
Total	215	358.722		

[a] Only F ratios greater than unity are indicated. No asterisks indicate probability >.05 (not significant). Two asterisks indicate probability <.01; three asterisks indicate probability <.001.

[b] S is a random factor; all other factors are fixed.

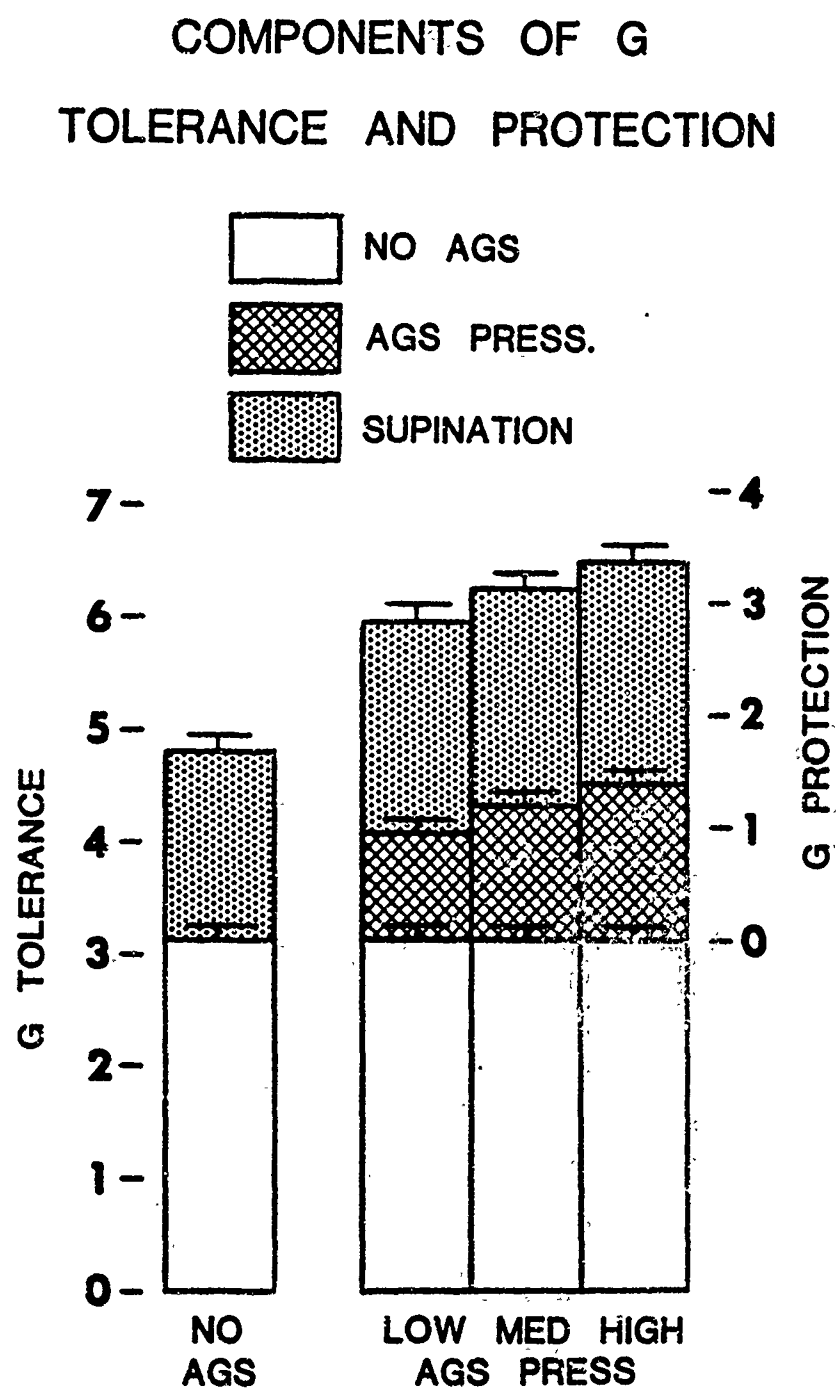

Figure 7. Components of G-tolerance and G-protection for various levels of AGS bladder inflation pressures.

0.06 G (upright) to 6.24 + 0.10 G (supine), an increase of 45 percent. It is therefore apparent that supination produces a quite significant increase in G tolerance, whether the AGS bladders are inflated or not.

Valve Outlet Pressure: This factor was second in importance with respect to affecting G tolerance, and from the viewpoint of practical application, was of primary interest. In general, as shown in Figures 7 and 8, the greater the valve outlet pressure, the greater the G tolerance for both the supine and upright body positions. In Figure 7, the segments of the bars ascribed to AGS bladder pressurization relate to the upright body position only, while the segments ascribed to supination include an interactive factor as well. Assuming the G protection (G tolerance with an inflated AGS and/or the supine body position minus upright G tolerance without AGS inflation) afforded by supination alone to be represented by that measured when no pressure was fed to the AGS bladders, Figure 7 includes additional protection of 0.22, 0.27, and 0.31 G as part of supination for, respectively, low, medium, and high valve outlet pressures. Protection afforded by some sort of synergistic effect, when two or more G protective techniques are simultaneously applied, is further discussed later in this report.

Paired t-tests were made to compare the differences in G tolerance for the three levels of SCAG valve outlet pressure across all other independent variables (subject, body position, SCAG valve mode of operation, and G onset time). The results of these tests are shown in Table 6. The null hypothesis tested here was that the mean difference in G tolerance for any two levels of SCAG valve outlet pressure was equal to zero. As shown by the entries in the table, the null hypothesis was emphatically rejected for all three possible comparisons. These findings therefore lend support to the proposition that the levels of SCAG valve outlet pressure used in this study were associated with distinct differences in G tolerance.

Based on a linear, first order model to describe the relationship between G tolerance and SCAG valve outlet pressure, and using the method of least squares, estimates were made of the slope and Y-intercept of the fitted straight lines for the upright and supine body positions (Figure 8). The means of G tolerance for the B and I modes ("Mode" was shown in Table 4 to be a non-significant factor as a variation source) were combined with G tolerance values for the no valve outlet pressure conditions to construct the analysis of variance summarized in Table 7. The residual sum of squares was divided into "pure error" and "lack of fit", the latter with respect to fitting the data to the linear model. The fact that the "lack of fit" mean squares for both body positions were not significant indicates the adequacy of the model and substantiates the use of the residual mean square to evaluate regresion as the source of variation (5). As shown in the table, overall regression was a very highly signficant source of variation. The maximum R^2 obtainable with these data was about 50 percent for the upright case and 38 percent for the supine. The values of R^2 actually attained by the fitted model have almost the same values, thereby accounting for 96 percent (upright) and 99 percent (supine) of the fit.

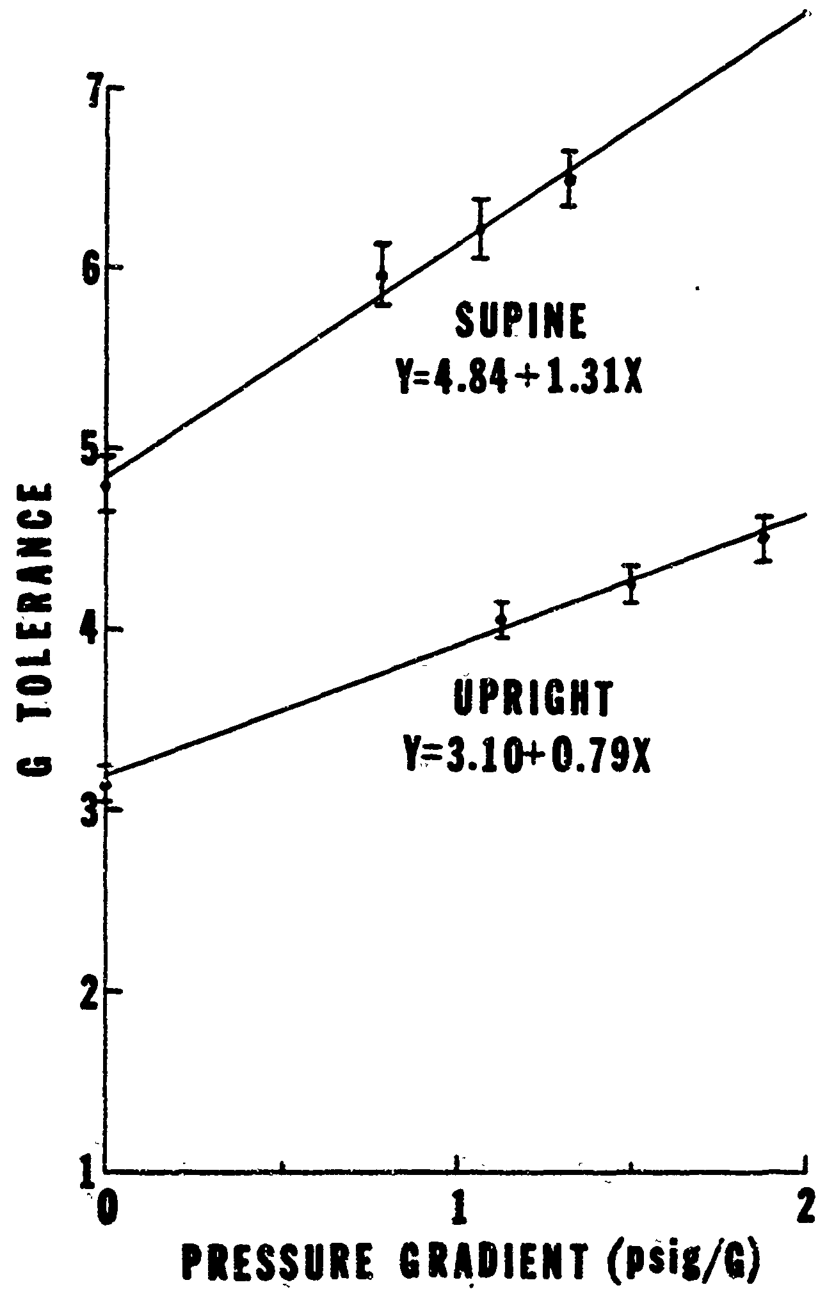

Figure 8. Best fit regression lines for G-tolerance on SCAG valve outlet pressure gradient (psig/G).

Table 6. Comparisons of G Tolerance Differences for SCAG Valve Outlet Pressures Across All Other Independent Variables

	SCAG Valve Outlet Pressures: Medium	SCAG Valve Outlet Pressures: High
Low	$\bar{D} = 0.24$ $s_{\bar{D}} = 0.06$ $t = 4.09$ $p < .001$	$\bar{D} = 0.56$ $s_{\bar{D}} = 0.07$ $t = 7.44$ $p < .001$
Medium		$\bar{D} = 0.25$ $s_{\bar{D}} = 0.06$ $t = 4.03$ $p < .001$

Abbreviations: $\bar{D}$ = mean difference in G tolerance between higher lower SCAG valve outlet pressures
$s_{\bar{D}}$ = standard error of the mean difference, $\bar{D}$
t = value of paired t-test (two-tailed) for 71 degrees of freedom
p = probability of t value

Table 7. Analysis of Variance Showing Regression of G Tolerance on SCAG Valve Outlet Pressure

UPRIGHT

Source	df	Sum of Squares	Mean Square	F	P
Regression	1	22.077	22.077	64.58	<.001
Residual	70	24.272	0.342		
Lack of Fit	2	1.035	0.527	1.54	NS*
Pure Error	68	23.237	0.342		
Total (corr.)	71	46.349			

Max. R^2 = (46.349 - 23.237)/46.349 = 0.499
R^2 attained by fitted model = 22.077/46.349 = 0.476
0.476/0.499 x 100 = 96% explained

SUPINE

Source	df	Sum of Squares	Mean Square	F	P
Regression	1	30.333	30.333	42.73	<.001
Residual	70	49.692	0.710		
Lack of Fit	2	0.260	0.130	0.18	NS
Pure Error	68	49.432	0.727		
Total (corr.)	71	80.025			

Max. R^2 = (80.025 - 49.432)/80.025 = 0.382
R^2 attained by fitted model = 30.333/80.025 = 0.379
0.379/0.382 x 100 = 99% explained

*NS indicates not significant ($p > .05$)

Inferences about the two parameters (slope and Y-intercept) of the model were made for both the upright and supine body positions (5). Table 8 summarizes the pertinent information. Although the 95 percent confidence intervals of the upright and supine Y-intercepts do not overlap, those of the two slopes overlap slightly. A t-test to evaluate the hypothesis of no difference between slopes yielded a value of 1.8986 for 140 degrees of freedom, just short of the value of 1.96 needed for rejection of the hypothesis at the $p = .05$ level. As shown in Table 6, the hypotheses were rejected that both parameters were equal to zero.

G Onset Time: Table 4 contains data showing the effect of G onset time. For the condition of no AGS bladder pressure, one way analyses of variance were made to evaluate the effect of G onset time on G tolerance; these are shown in Table 9 for the upright and supine body positions. For both these body positions, G onset time is not significant. Note the much greater variance present when the subjects were supinated. This information is also evident from examining Figure 9. Analyses of variance were also made for the effect of G onset time on G tolerance when the AGS bladders were inflated. Data entries for the upright body position were the means of B and I mode values, while data entries for the supine body position were the individual values (Table 10). Again, for both body positions, G onset time is not statistically significant. However, because the F value for the supine body position does approach the value necessary for significance at the $p = .05$ level (3.10), paired t-tests were made on this data. Comparing G tolerance for 2 and 8 s G onset times, a value of $t_{35} = 4.19$ was calculated, with $p < .001$. Comparing 4 and 8 s G onset times, $t_{35} = 2.22$, with $p < .05$; for 2 and 4 s G onset times, $t_{35} = 1.82$, with $.05 < p < .10$. Therefore, when the G onset times were separated by only 2 s, apparently there was no difference in mean G tolerance. Doubling the difference in G onset time produced a significant decrease in mean G tolerance, and tripling the difference caused a very highly significant decrease in mean G tolerance. The relations between G tolerance and G onset times are shown in Figure 9.

<u>AGS Comfort Assessment</u> Mean AGS comfort scores for each subject are shown in Table 11. Paired t-tests showed no significant difference in mean AGS comfort scores between Modes B and I in the upright body position ($t_5 = 0.21$, $p > 0.8$), and in the supine body position ($t_5 = 1.45$, $0.2 < p < 0.5$). The difference in mean comfort scores for the upright and supine body positions was also evaluated using the paired t-test and found to be non-significant ($t_5 = 0.10$, $p > 0.8$). The overall mean comfort scores of the subjects, shown in Table 11, were then subtracted from their individual comfort scores to obtain adjusted comfort scores. Mean adjusted comfort scores are presented in Table 12 for the conditions of this study. Two-way analyses of variance were made on the adjusted comfort scores to determine the relative effect of AGS bladder pressure and G onset time. The results of these analyses for each of the subjects are shown in Figure 10. While AGS bladder pressure played a statistically significant role with

Table 8. Inferences about Two Model Parameters, β_0 and β_1[a], for the Regression of G Tolerance on SCAG Valve Outlet Pressure

	Body Position	
	Upright	Supine
95% C.I.[b]	$2.8401 \leq \beta_0 \leq 3.3645$ $0.5908 \leq \beta_1 \leq 0.9864$	$4.4641 \leq \beta_0 \leq 5.2147$ $0.9086 \leq \beta_1 \leq 1.7098$
$H_0: \beta_0 = 0$[c]	23.6636[d]	25.7964
$H_0: \beta_1 = 0$	7.9721	6.5362

[a] β_0 and β_1 are the model parameters for b_0, the Y-intercept, and b_1, the slope, of the linear regression curve.

[b] Confidence Interval

[c] The null hypothesis that the parameter equals zero.

[d] Calculated value of t. The value of t for 70 degrees of freedom at the $p \approx .05$ level is approximately 2.

Table 9. Analyses of Variance of G Tolerance for G Onset Times without AGS Bladder Inflation

Source	df	Sum of Squares	Mean Square	F	P
		UPRIGHT			
G Onset Time	2	0.02	0.01	0.06	NS*
Error	15	2.88	0.19		
Total	17	2.90			
		SUPINE			
G Onset Time	2	0.30	0.15	0.29	NS
Error	15	7.69	0.51		
Total	17	7.99			

*NS indicates not significant (p>.05)

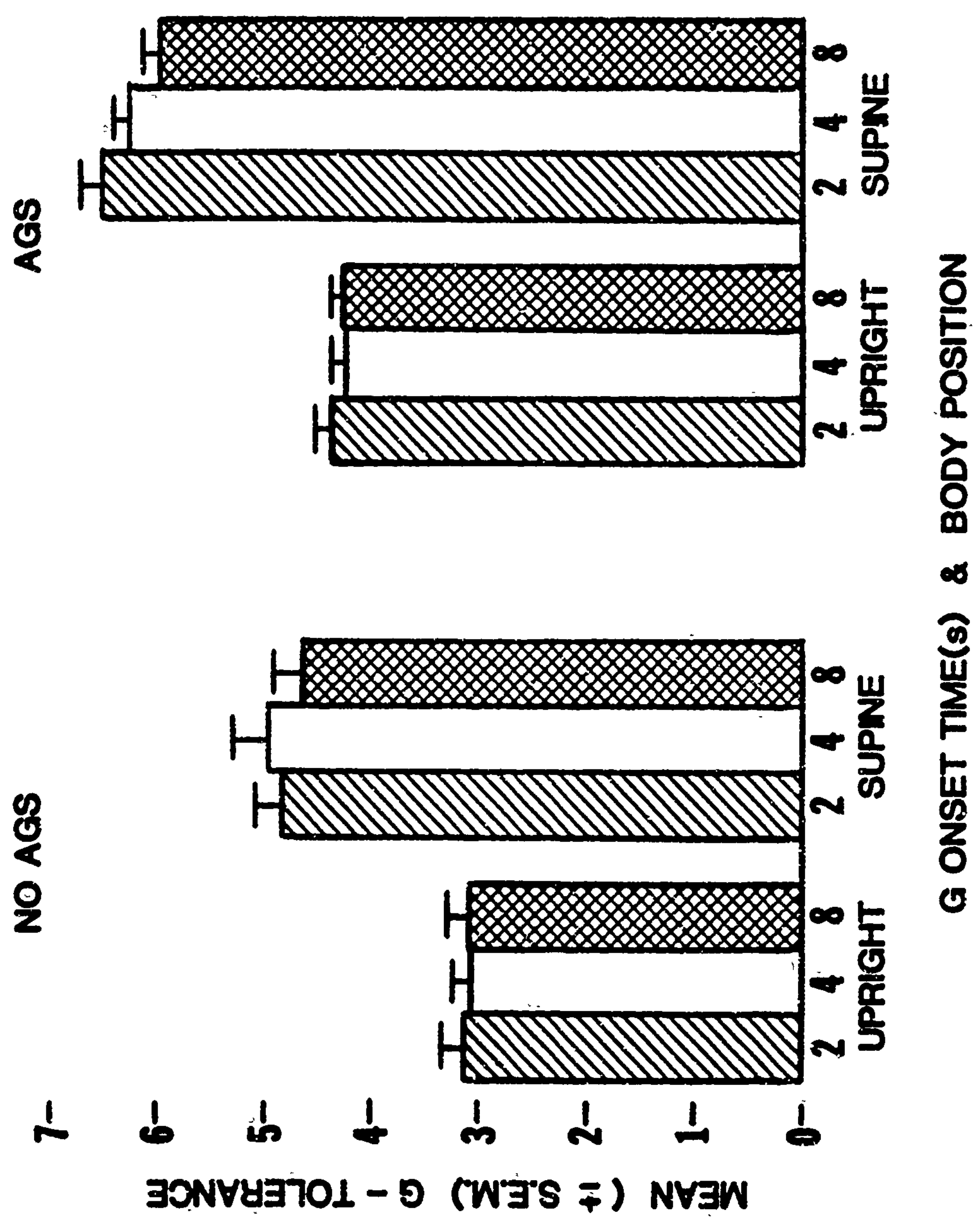

Figure 9. Relation G-tolerance, G onset time, and body position.

Table 10. Analyses of Variance of G Tolerance for G Onset Times with AGS Bladder Inflation

Source	df	Sum of Squares	Mean Square	F	P
		UPRIGHT			
G Onset Time	2	0.19	0.10	0.22	NS*
Error	51	21.93	0.43		
Total	53	22.12			
		SUPINE			
G Onset Time	2	5.11	2.55	2.66	NS
Error	105	100.69	0.96		
Total	107	105.80			

*NS indicates not significant (p>.05)

Table 11. Mean AGS Comfort Scores (N = 9)

	SUBJECT					
	1	2	3	4	5	6
Upright						
Mode I*	50.33	47.56	56.11	70.56	68.33	62.78
Mode B	67.22	49.44	54.44	61.11	78.33	50.83
Supine						
Mode I	67.78	46.67	57.78	66.11	51.89	55.56
Mode B	68.89	57.56	50.00	67.22	61.11	70.83
Mean	63.56	50.31	54.58	66.25	64.92	60.00

* Mode of SCAG valve operation. See text for explanation.

Table 12. Adjusted AGS Comfort Scores* (Mean ± S.E.M., N = 6)

Valve Outlet Press	UPRIGHT G Onset Time (s) 2 Mode I	B	4 Mode I	B	8 Mode I	B	SUPINE G Onset Time (s) 2 Mode I	B	4 Mode I	B	8 Mode I	B
Low	7.50 ±11.15	22.50 ±4.62	13.33 ±7.25	9.58 ±10.54	-7.50 ±11.01	6.67 ±10.78	18.33 ±4.02	17.00 ±3.54	15.00 ±5.11	20.83 ±4.56	11.67 ±2.12	16.67 ±7.50
Medium	9.17 ± 6.49	19.17 ±6.44	0.50 ±4.58	-3.33 ±4.92	-10.83 ±6.64	-15.00 ±11.69	4.17 ±10.90	11.67 ±5.82	10.33 ± 9.34	-5.83 ±7.01	4.17 ±5.70	-2.50 ±7.59
High	-11.17 ± 6.11	-21.67 ±9.55	-5.00 ±7.53	-2.50 ±11.17	-2.50 ±11.75	-13.33 ±9.72	-19.50 ±13.68	-13.33 ±14.59	-39.17 ± 7.12	-10.33 ±7.74	-26.33 ±6.01	-10.83 ±9.97

* Adjusted by subtracting each subject's overall mean score from his individual scores.

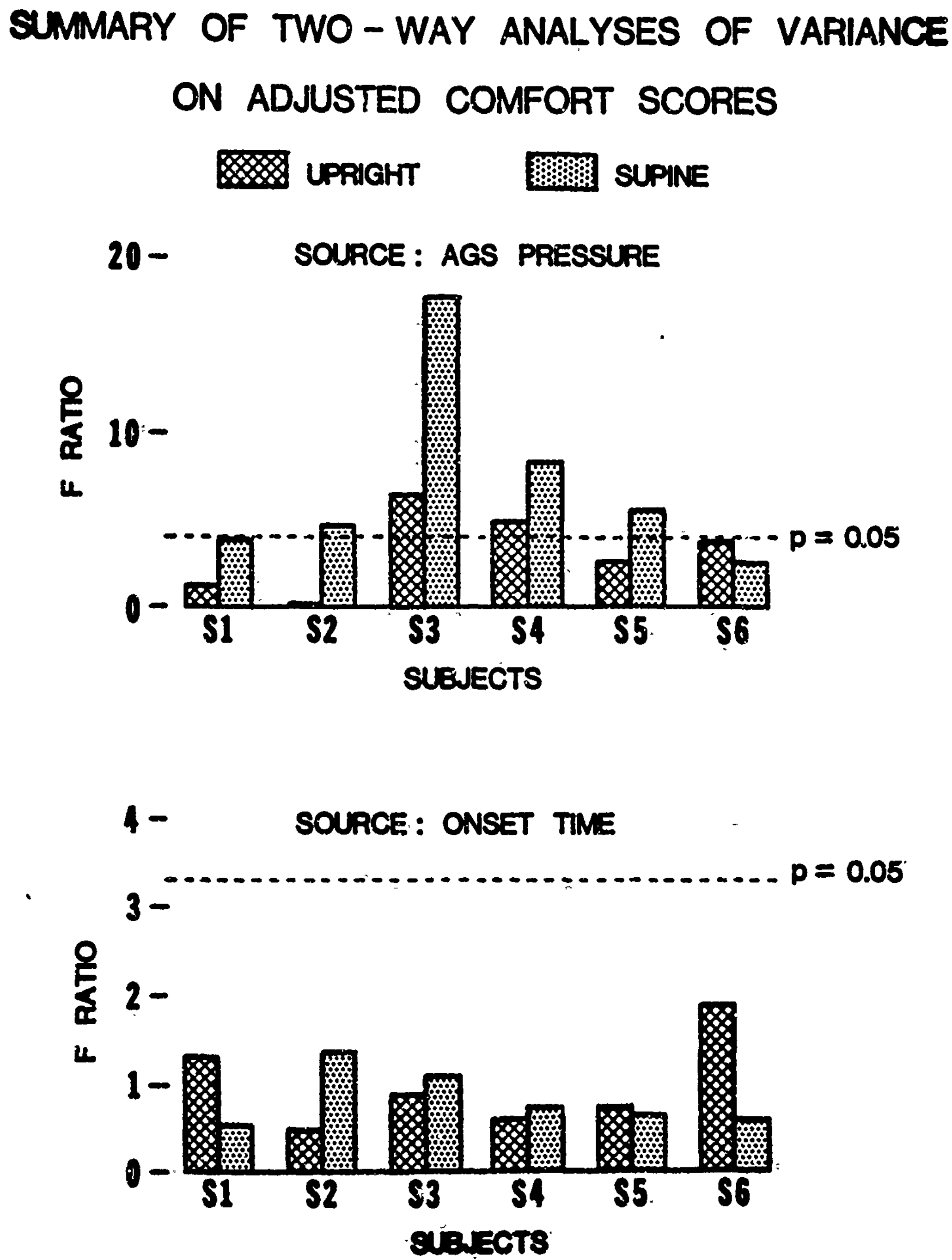

Figure 10. Relative effects of AGS bladder pressure and G onset time on adjusted comfort scores.

respect to adjusted comfort scores for most of the subjects, G onset time was not a significant factor for any of the subjects.

Mean adjusted comfort scores and their standard errors for both body positions and for the three levels of SCAG valve outlet pressure are shown in Figure 11. The zero point on the horizontal scale corresponds to the overall mean comfort score of about 60. This lies somewhat less than half way between the adjective ratings of "fair" and "good". As expected, at the high levels of AGS bladder pressure, discomfort increased and the scores were accordingly reduced. The converse occurred with the low levels of AGS bladder pressure.

A review of the comments made by the subjects regarding AGS comfort revealed that after about one-third of the G tolerance limit runs, adverse remarks were made. Following the other two-thirds, AGS comfort was commented upon favorably or not mentioned. Adverse comments were concerned primarily with "tightness" or "pressure" of the AGS over those parts of the body situated under the bladders. About 57 percent of adverse comments were made after runs in the upright body position, and the remaining 43 percent after runs in the supine body position. Although only about 29 percent of all the G tolerance runs were made with high levels of AGS bladder pressure, about 60 percent of these runs were accompanied by adverse comments regarding comfort. Another 14 percent of the high pressure runs were rated poor or very poor with respect to AGS comfort, with no additional remarks. About 13 percent of the adverse comments were made following G tolerance runs where there were low AGS bladder pressures, and once when there was no bladder pressure. The remaining 27 percent of adverse comments followed runs with medium bladder pressures. The adverse comments were not distributed equally among subjects. The most vocally critical subject made almost three times the number of adverse remarks as the least vocally critical. Discomfort during high bladder pressure runs constituted about a third of the comments made by two subjects, about half made by three subjects, and about two-thirds made by the remaining subject.

<u>DISCUSSION</u> The results obtained in this study, and others like it, depend to a great extent upon the individuals who volunteer to participate as subjects. As expected, these persons differ substantially in their physical characteristics and also show considerable variation in G tolerance. Other factors which may affect G tolerance, and which lie entirely outside the purview of the investigator, may originate from activities or behavior in which the subject participates when he leaves the laboratory at the end of the working day. Unfortunately, because of expenditures required to conduct human centrifuge tests and because of limitations on the availability of qualified subjects and of the centrifuge facility itself, the number of runs devoted to any one study is necessarily quite limited. Thus, the combination of intra-subject variability and limitations on the amount of data which can be collected make it quite difficult to detect small differences in effects which may, nevertheless, be present. For these reasons, the question of whether the small increments in G protection resulting from the simultaneous use of

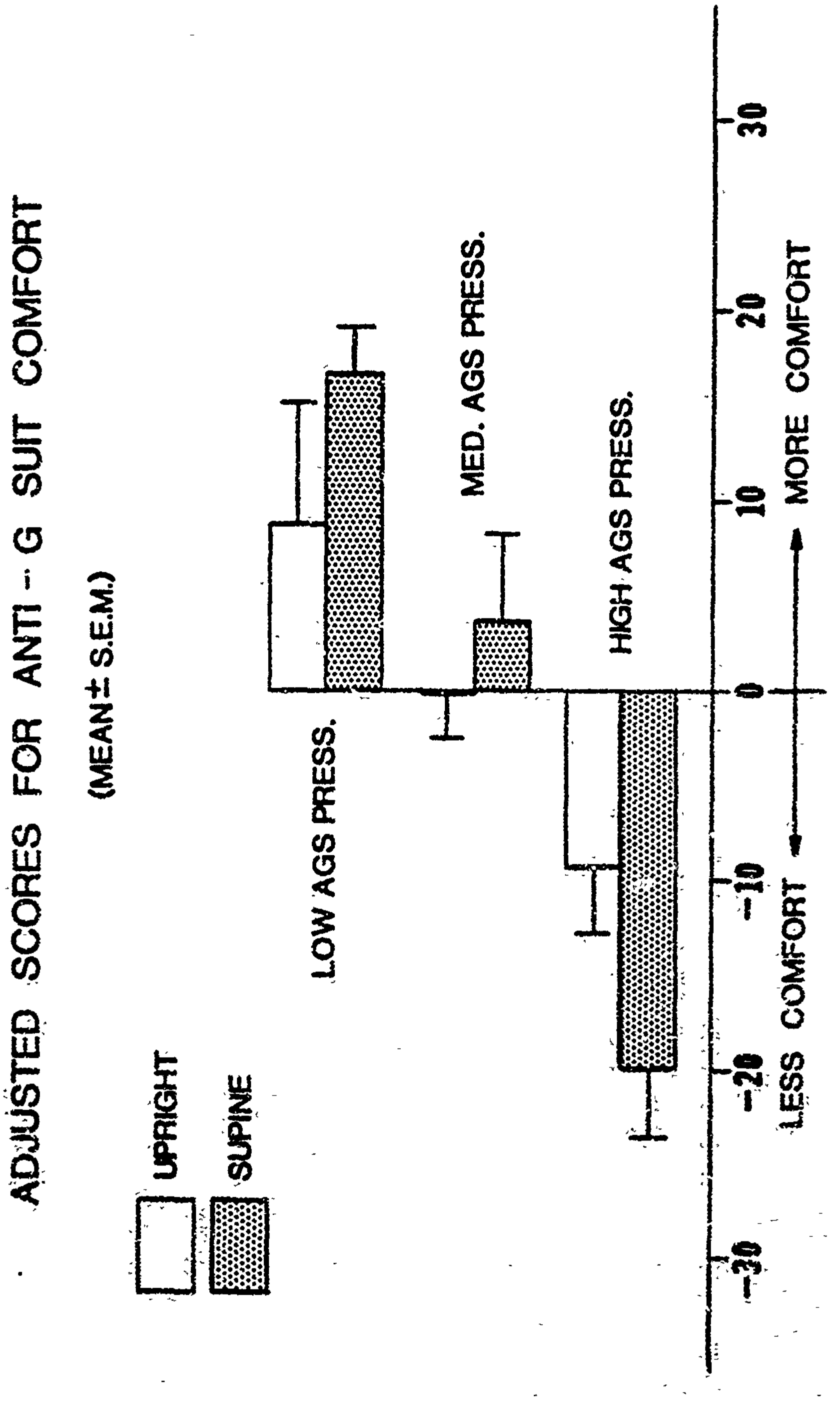

Figure 11. Mean adjusted comfort scores for AGS bladder pressure levels and body positions.

the AGS and supination, as described earlier, are additive or not, is of particular interest.

In a recent paper, Cohen showed that a simple additivity model best predicted acceleration tolerance provided by simultaneously combining various acceleration protection techniques (2). In fact, when a combination of protective techniques was used, a higher G tolerance was obtained than when the G tolerance due to each of the several component protective techniques in the combination were added, but the difference in G tolerance between the measured combined effect and the calculated added effect was not statistically significant. Crosbie compared G protection afforded by the SCAG valve and the standard anti-G valve for upright subjects while relaxed or performing the M-1 straining maneuver (4). An analysis of his data shows a pronounced difference in G tolerance resulting from the combined effect of the M-1 maneuver and AGS bladder pressurization, especially with the SCAG valve, but again, no statistical difference can be demonstrated from the calculated sum of the individual tolerance components.

Since the equipment and techniques used by Cohen and Crosbie were essentially the same as those described in the present paper, a similar analysis of the protection afforded at the various AGS pressure levels was made for each of the subjects of this study in the upright and supine body positions. As shown in Figure 12, except for subjects 4 and 6, the others exhibited a higher G tolerance for the combination of AGS and supination than when the tolerances obtained separately for AGS and for supination were added. For the two subjects mentioned, just the reverse was found at all three AGS pressure levels. The mean difference for all subjects showed a G protection advantage when a combination of protective techniques was used, but this difference was not statistically significant at any of the three AGS pressure levels (for low AGS pressure, $t_5 = 1.34$, $p > 0.2$; for medium AGS pressure, $t_5 = 1.46$, $p > 0.1$; and for high AGS pressure, $t_5 = 1.09$, $p > 0.2$).

Therefore, the present data confirms what was found in the previous two studies cited above, and supports the concept of the additivity of G protective techniques. In any case, from the practical viewpoint, there have been no indications that any one G protective technique interferes with, or somehow diminishes the effectiveness of another employed at the same time. The least effect observed when two or more such techniques are combined is additivity; the possibility that greater control and precision in conducting acceleration studies may demonstrate a significant synergistic effect is therefore primarily one of a more basic interest.

Although the subjects who participated in this study were repeatedly reminded to remain "relaxed" throughout the period of acceleration runs, it is doubtful first, that the subjects were actually relaxed, and second, that their degree of relaxation remained constant from run to run. No matter how experienced a centrifuge rider a subject may be, there can be little doubt that the act of being strapped into a seat, being completely enclosed and isolated in a gondola, and listening to the dialogue and countdown prior to an acceleration run lead to some apprehension

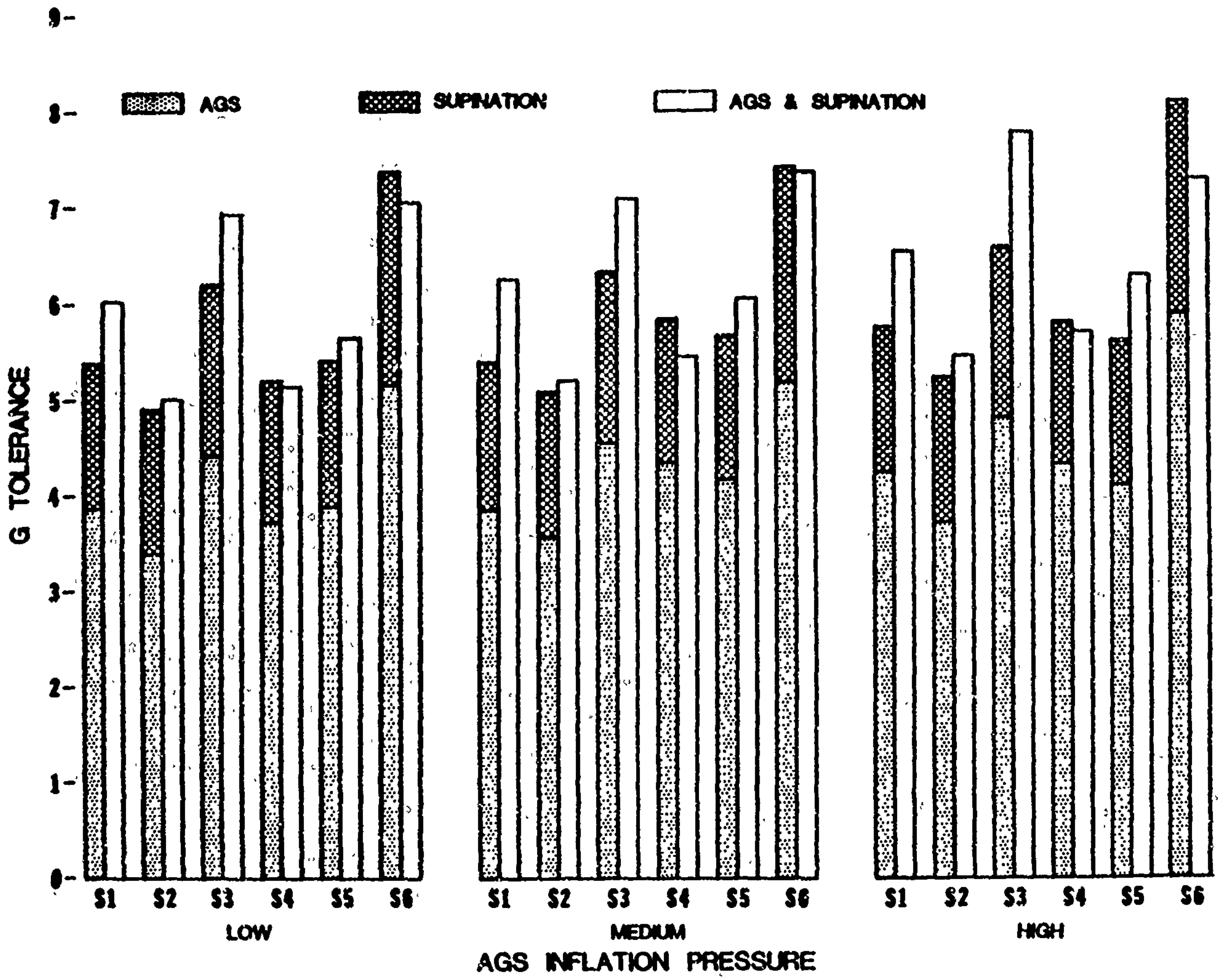

Figure 12. Comparison for individual subjects of contributions to G-tolerance for AGS and supination separately (shaded bars) and simultaneously combined (clear bars).

and tension. In fact, as reported by Webb (6), and often observed by others, there is a distinct increase in heart rate which can be measured before the start of a centrifuge acceleration run, and this increase is greater when the subject anticipates his exposure to higher G levels. To even remain in the upright or supinated body position at 1 G requires some degree of muscular tension, which would be expected to increase considerably with applied G. Probably the ultimate extent of voluntary muscular tension is exerted when subjects perform the M-1 respiratory maneuver during exposure to high G levels. None of the subjects in the present study was observed to have performed this maneuver, although normal respiratory and arm movements were modified during G. No artifacts were seen on the ECG recordings which could be ascribed unequivocally to muscular activity. It appears, therefore, that although not completely relaxed during the course of exposure to the G levels applied in this study, our subjects maintained sufficient muscular tension to retain their posture and to perform the rather precise wrist and arm movements required to control the LED display which measured peripheral vision.

Equation (1) is based on the assumptions that the simple hydrostatic model of the cardiovascular system is valid and that the mechanism of G protection provided by the AGS remains unchanged when the body position is significantly altered by supination. If these assumptions hold, then the degree of protection afforded by the AGS when pressurized in accordance with equation (1) should be the same for both body positions. In order to test this hypothesis, a comparison was made, using the paired t-test, between AGS protection (G tolerance using the AGS minus G tolerance without AGS inflation, for each set of corresponding experimental conditions) in the supine and upright body positions for each of the outlet pressure levels. Table 13 shows the results of this comparison. Since none of the t values calculated is statistically significant, the hypothesis of no difference in G protection between the supine and upright body positions cannot be rejected. Therefore, the data obtained in this study are consistent with the application of equation (1) for determining AGS bladder pressurization, at least where the seat back angle equals 15 degrees and 60 degrees.

As explained earlier, the end result of using what is referred to here as the B mode of SCAG valve operation was to decrease the lag in AGS abdominal bladder inflation by several hundred milliseconds, as compared to the I mode. Under the conditions of the tests as described, this small difference in timing of abdominal bladder inflation had no discernible effect on G protection nor on AGS comfort. In this connection, it should be noted that the maximum mean G onset rate (calculated by dividing the difference between plateau and baseline G by G onset time) was 1.75 G/s in the upright body position and 2.75 G/s in the supine body position. These G onset rates, while rapid, may have been insufficient to demonstrate the added protection that earlier inflation of the abdominal bladder may provide. Preinflation of the AGS, i.e., bladder inflation before the onset of applied G, has been used to reduce the volume of air required to fill the bladders, and hence shorten bladder filling time. Thus, a

Table 13. Comparison of AGS Protection in the Upright and Supinated Body Positions

AGS Inflation Pressure	Supine minus Upright G Protection		Paired t-test		
	Mean	SEM	t	df	P
Low	0.22	0.16	1.39	17	NS*
Medium	0.27	0.15	1.81	17	NS
High	0.31	0.19	1.68	17	NS

*NS indicates not significant (p>.05)

recently developed anti-G valve used by the U.S. Air Force, designated HFRP, allows for the use of 0.2 psi at 1 G for preinflation (1), and a preinflation pressure of only 0.05 psi has been shown to be effective with the SCAG valve in decreasing the lag in bladder pressurization with the onset of G (2). Because some pilots object to having their AGS even partially inflated at 1 G, this procedure was not followed in this study. Since the lag in bladder inflation between the B and I modes caused no detectable differences in the dependent variables, it is doubtful if changes due to preinflation would have been significant.

Selection of the low and high levels of SCAG valve outlet pressures was arbitrary. It was desired to have sufficient differences from the medium level to obtain observable changes in the dependent variables, without incurring pain in the high level case or totally ineffective G protection in the low level case. The interactions of SCAG valve outlet pressure with G onset time and mode of valve operation were unpredictable. A review of the literature dealing with AGS bladder pressurization levels failed to provide much guidance, because of rather marked differences in equipment and techniques used by the various investigators. However, it appears from the mean adjusted comfort scores that serious pain was avoided with the high pressure levels, although considerable discomfort was experienced at times, especially in the supine body position. The medium pressure level was evidently close to what the subjects experienced as adequate comfort. For the upright body position, the medium level was somewhat greater than the upper limit of valve outlet pressure allowed in the military specification (see Figure 5). The low SCAG valve outlet pressure was the one which overlapped, to the greatest extent, with the pressure range prescribed in the military specification.

If the adjusted comfort score of zero, which in Figure 11 appears reasonable for the upright body position, is also accepted for the supine body position, then it would seem that a slightly greater bladder pressure could have been used for the middle level, supine body position. The large swings in comfort seen for the high and low AGS bladder pressures for the supine body position may be an indication that the selection of 25 percent of the middle level pressure gradient could have been reduced by 5 or 10 percent in determining the low and high pressure gradients to apply. Of course, if this were done, then differences in G tolerance due to these reduced pressure gradients would be more difficult to detect.

The relevance of AGS comfort ratings and comments to the situation in actual aircraft flight is probably debatable. In the laboratory situation, the subject has the task of concentrating on how the AGS feels, and he is therefore probably more critical in his evaluation than a pilot would be, especially if the latter were preoccupied with executing a series of air combat maneuvers. This problem can only be resolved by flight testing the SCAG valve under controlled conditions which are designed to duplicate operational aircraft maneuvers of interest. Fortunately, the SCAG valve can be readily programmed to produce a variety of outlet pressure responses, and it is contemplated that such flight tests will commence in the near future.

SUMMARY G tolerance was increased when relaxed subjects riding a centrifuge were supinated (seat back angle of 60 degrees), as compared to when they sat upright (seat back angle of 15 degrees). When wearing an anti-G suit (AGS) with inflated bladders, G tolerance increased in both the supine and upright body positions. These increases were linear with increases in AGS bladder pressure. Changing G onset time by a factor of two and four showed a consistent effect only for the supine body position with AGS bladder inflation: G tolerance decreased as G onset time increased. Changing the mode of operation of a recently designed servo controlled anti-G valve regulating AGS bladder pressure had no effect on G tolerance nor on AGS comfort. Comfort was also unaffected by G onset time, but high AGS bladder pressures reduced AGS comfort scores and elicited adverse comments. Results of this study supported the hypothesis that G protection provided by simultaneously applied anti-G techniques is additive. They also were compatible with the hydrostatic model of the circulatory system with respect to the pressure in the AGS bladders required to provide G protection when body posture was changed.

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APPENDIX A

Definition of Acceleration   Figure 13 illustrates the components of acceleration and the terminology as used in this report (8). Three mutually perpendicular accelerations, shown as A_t, A_v, and A_r, act on the subject when he rides the DFS: A_t, the tangential acceleration, is proportional to the angular acceleration of the DFS arm, and is therefore of significance whenever the angular velocity of the arm changes; A_v, the downward acceleration due to gravity remains unchanged at 1g before, during, and after the centrifuge run; A_r, the centrifugal acceleration, changes as the square of the angular velocity of the arm, and tends to displace the subject's body and its contents footward, when the subject rides with his head directed toward the center of arm rotation. The resultant acceleration, G, is what is referred to as "G" or "acceleration" in this report.

When the subject is seated "upright" (seatback angle = 15 degrees), before the centrifuge arm is turned as well as after it comes to rest, only A_v acts on the subject, and therefore he is subjected to 1 G. Since this acceleration is applied essentially along the long axis of his spine, the inertial loading he experiences is 1 Gz (by definition). By manipulation of the DFS gimbals, the G applied to the upright-seated subject during the

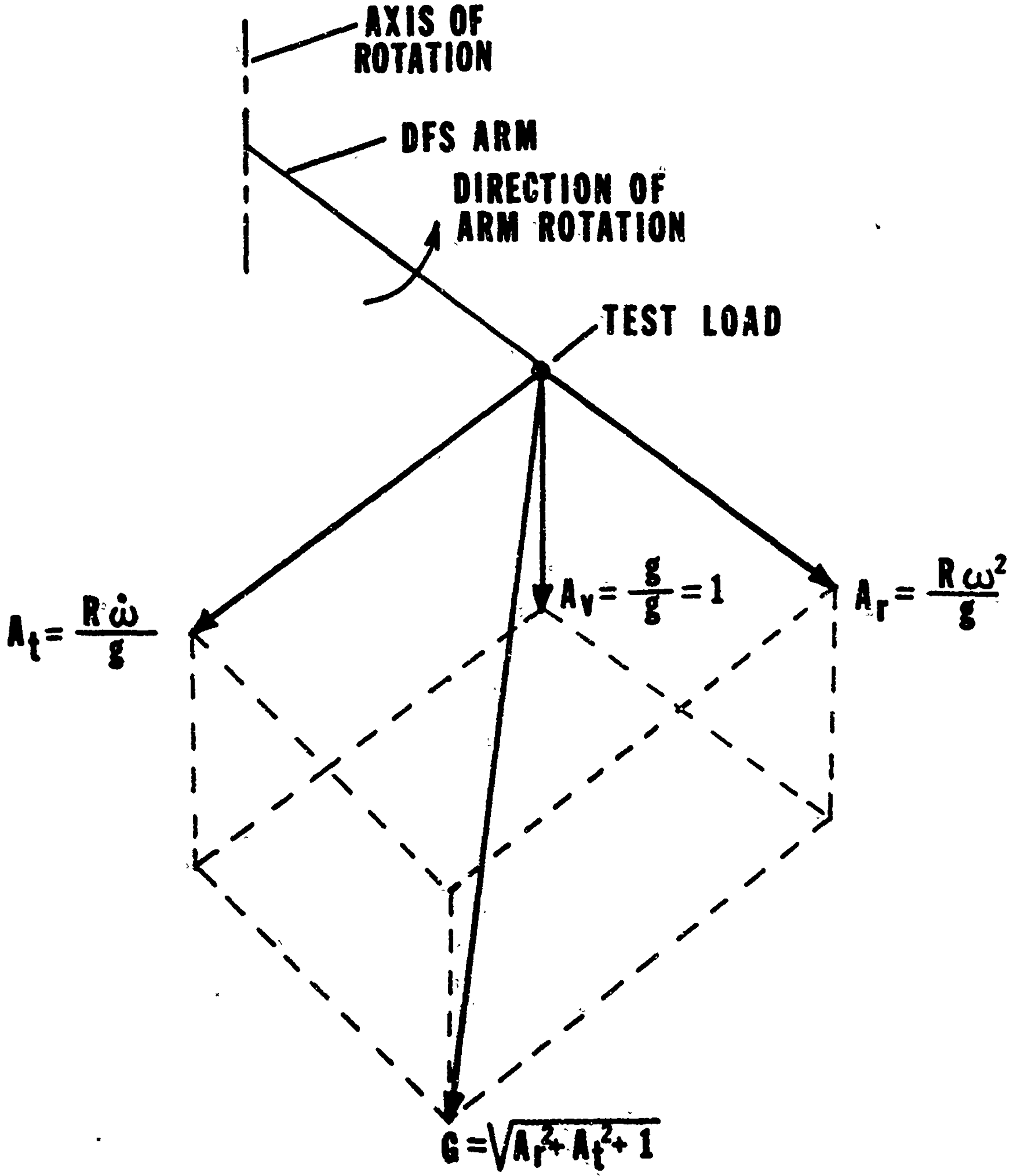

Figure 13. Diagram showing G nomenclature.

acceleration profile is maintained parallel to the long axis of his spine, resulting in a Gz inertial loading which is numerically equal to G. When the subject is placed in the supinated body position (seatback angle = 60 degrees), before and after rotation of the centrifuge arm, only A_v acts on the subject and he is therefore subjected to 1 G. However, because only a fraction (about 70 percent) of A_v is directed parallel to his spine, he experiences a head-to-foot inertial load of about 0.7 Gz.[1] During the acceleration profile, when the centrifuge arm is rotating, the subject is positioned by the DFS gimbals to experience a Gz inertial load which continues to be approximately 70 percent of the applied G. The distinction between the resultant acceleration, G, and the head-to-foot inertial load (Gz) it produces, cannot be neglected.

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[1] The actual fraction depends on several factors, including the anatomical arrangement of the subject's cardiovascular tree.

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